

$\eta'K$ puzzle of B meson decays and new physics effects in the TC2 model

Zhenjun Xiao^(1,2) Wenjun Li¹, Libo Guo⁽³⁾ and Gongru Lu⁽¹⁾

1. Department of Physics, Henan Normal University, Xinxiang, 453002 P.R. China. *

2. Department of Physics, Peking University, Beijing, 100871 P.R. China.

3. Department of Physics, Wuhan University, Wuhan, 430000 P.R. China.

February 1, 2008

Abstract

Using the low energy effective Hamiltonian with the generalized factorization, we calculate the new physics contributions to $B \rightarrow \pi^+\pi^-$, $K\pi$ and $K\eta'$ in the Topcolor-assisted-Technicolor(TC2) model, and compare the results with the available data. By using $F_0^{B\pi}(0) = 0.20 \pm 0.04$ preferred by the CLEO data of $B \rightarrow \pi^+\pi^-$ decay, we find that the new physics enhancements to $B \rightarrow K\eta'$ decays are significant in size, $\sim 50\%$ with respect to the standard model predictions, insensitive to the variations of input parameters and hence provide a simple and plausible new physics interpretation for the observed unexpectedly large $B \rightarrow K\eta'$ decay rates.

PACS numbers: 13.25.Hw, 12.15.Ji, 12.38.Bx, 12.60.Nz

*Mailing address

In two-body charmless hadronic B meson decays, new physics beyond the standard model (SM) may manifest itself through large enhancements to those penguin-dominated decay modes: decays which are expected to be rare in the SM are found to have large branching ratios. These potential deviations may be induced by the virtual effects of new physics through penguin and/or box diagrams [1, 2, 3, 4].

In the framework of the SM, the two-body charmless hadronic decays $B \rightarrow h_1 h_2$ [where h_1 and h_2 are the light pseudo-scalar (P) and/or vector(V) mesons] have been studied systematically by many authors [5, 6, 7, 8, 9]. On the experimental side, fourteen $B_{u,d} \rightarrow PP, PV$ decay channels have been observed by CLEO, BaBar and BELLE Collaboration [10, 11, 12, 13, 14]:

$$B \rightarrow \pi^\pm \pi^\mp, K\pi, K\eta', \rho^\pm \pi^\mp, \rho^0 \pi^\pm, \omega \pi^\pm, K^* \eta, K^\pm \pi^\mp, \phi K^\pm. \quad (1)$$

By comparing the theoretical predictions with experimental measurements one finds the following main points:

- The effective Hamiltonian with generalized factorization approach generally works well to interpret the observed pattern of branching ratios. The penguin effects are clearly observed[15].
- There may exist a problem to accommodate the data of $\pi\pi$ and $K\pi$ simultaneously[16].
- The $\eta'K$ puzzle: the $B \rightarrow K\eta'$ decay rates are much larger than what one ordinarily expected in the SM [12, 16].

Since 1997, the unexpectedly large branching ratio of $B \rightarrow K\eta'$ has stimulated much interests in literature [17, 18, 19, 20, 21]. In order to accommodate the data, one may need an additional contribution unique to the η' meson in the framework of the SM, or new physics enhancements from new physics models beyond the SM to explain the $B \rightarrow K\eta'$ puzzle [12]. In a previous paper[22], we considered the second possibility and calculated the new physics effects on the branching ratios and CP-violating asymmetries of fifty seven $B \rightarrow PP, PV$ decay modes in the Topcolor-assisted Technicolor (TC2) model[23], and found that the new physics enhancement to the penguin-dominated decay modes can be significant. In another paper[24], we calculated the new physics contributions to branching ratios of seventy six $B \rightarrow h_1 h_2$ decay modes in the general two-Higgs-doublet models (models I, II and III).

In this letter, we concentrate on the new physics contributions to seven observed B decay modes: $B \rightarrow \pi^\pm \pi^\mp, K\pi$ and $B \rightarrow K\eta'$ in the TC2 model. Particular attention is devoted to the details of $B \rightarrow K\pi$ and $B \rightarrow K\eta'$ decays when a smaller $F_0^{B\pi}(0) = 0.20 \pm 0.04$ instead of the ordinary $F_0^{B\pi}(0) = 0.33$ are used.

The effective Hamiltonian for the two-body charmless decays $B \rightarrow h_1 h_2$ are now known at next-to-leading order (NLO) [25, 8, 9]. The standard theoretical frame to calculate the

inclusive three-body decays $b \rightarrow s\bar{q}q^1$ is based on the effective Hamiltonian[8],

$$\mathcal{H}_{eff}(\Delta B = 1) = \frac{G_F}{\sqrt{2}} \left\{ \sum_{j=1}^2 C_j \left(V_{ub}V_{us}^* Q_j^u + V_{cb}V_{cs}^* Q_j^c \right) - V_{tb}V_{ts}^* \left[\sum_{j=3}^{10} C_j Q_j + C_g Q_g \right] \right\}, \quad (2)$$

where the operator basis contains the current-current operators $Q_{1,2}$, the QCD penguin operators Q_{3-6} , the electroweak penguin operators Q_{9-10} and the chromo-magnetic dipole operator Q_g , the explicit expressions can be found easily for example in Ref.[8]. Following Ref.[8], we also neglect the effects of the electromagnetic penguin operator $Q_{7\gamma}$, and do not consider the effect of the weak annihilation and exchange diagrams. The coefficients C_i in Eq.(2) are the well-known Wilson coefficients. Within the SM and at scale M_W , the Wilson coefficients $C_1(M_W), \dots, C_{10}(M_W)$ at NLO level and $C_g(M_W)$ at LO level have been given for example in [25].

Following the same procedure as in the SM, it is straightforward to calculate the new γ^- , Z^0 - and gluonic penguin diagrams induced by the exchanges of unit-charged scalars, the technipion π_1^\pm, π_8^\pm and top-pion $\tilde{\pi}^\pm$ appeared in the TC2 model ².

After including the new physics (NP) contributions induced by new penguin diagrams, the Wilson coefficients $C_i(M_W)$ $i = 1, \dots, 10$ at NLO level and C_g at leading-order (LO) can be written as

$$C_1(M_W) = 1 - \frac{11}{6} \frac{\alpha_s(M_W)}{4\pi} - \frac{35}{18} \frac{\alpha_{em}}{4\pi}, \quad (3)$$

$$C_2(M_W) = \frac{11}{2} \frac{\alpha_s(M_W)}{4\pi}, \quad (4)$$

$$C_3(M_W) = -\frac{\alpha_s(M_W)}{24\pi} \left[E_0(x_t) + E_0^{NP} - \frac{2}{3} \right] + \frac{\alpha_{em}}{6\pi} \frac{1}{\sin^2 \theta_W} \left[2B_0(x_t) + C_0(x_t) + C_0^{NP} \right], \quad (5)$$

$$C_4(M_W) = \frac{\alpha_s(M_W)}{8\pi} \left[E_0(x_t) + E_0^{NP} - \frac{2}{3} \right], \quad (6)$$

$$C_5(M_W) = -\frac{\alpha_s(M_W)}{24\pi} \left[E_0(x_t) + E_0^{NP} - \frac{2}{3} \right], \quad (7)$$

$$C_6(M_W) = \frac{\alpha_s(M_W)}{8\pi} \left[E_0(x_t) + E_0^{NP} - \frac{2}{3} \right], \quad (8)$$

$$C_7(M_W) = \frac{\alpha_{em}}{6\pi} \left[4C_0(x_t) + 4C_0^{NP} + D_0(x_t) + D_0^{NP} - \frac{4}{9} \right], \quad (9)$$

$$C_8(M_W) = 0, \quad (10)$$

$$C_9(M_W) = \frac{\alpha_{em}}{6\pi} \left\{ 4C_0(x_t) + 4C_0^{NP} + D_0(x_t) + D_0^{NP} - \frac{4}{9} \right\}$$

¹For $b \rightarrow d\bar{q}q$ decays, one simply make the replacement $s \rightarrow d$.

²For more details of TC2 model[23] and the corresponding constraint on its parameter space from the data, one can see Refs.[23, 26, 27] and our previous paper [22]. For the sake of simplicity, we here do not present the details about the calculations of new penguin diagrams in the TC2 model, but the reader can find them in Ref.[22, 28].

$$+ \frac{1}{\sin^2 \theta_W} \left[10B_0(x_t) - 4C_0(x_t) + 4C_0^{NP} \right] \Big\} , \quad (11)$$

$$C_{10}(M_W) = 0 , \quad (12)$$

$$C_g(M_W) = -\frac{1}{2} \left[E'_0(x_t) + E_0^{NP} \right] , \quad (13)$$

where $x_t = m_t^2/M_W^2$, the functions $B_0(x)$, $C_0(x)$, $D_0(x)$, $E_0(x)$ and E'_0 are the familiar Inami-Lim functions which describe the contributions from the W -penguin and Box diagrams in the SM and can be found, for example, in Refs.[25, 4]. The functions C_0^{NP} , D_0^{NP} , E_0^{NP} and $E_0'^{NP}$ describe the new physics contributions to Wilson coefficients in the TC2 model as given in Ref.[22],

$$C_0^{NP} = \frac{1}{\sqrt{2}G_F M_W^2} \left[\frac{m_{\tilde{\pi}}^2}{4F_{\tilde{\pi}}^2} T_0(y_t) + \frac{m_{\pi_1}^2}{3F_{\pi}^2} T_0(z_t) + \frac{8m_{\pi_8}^2}{3F_{\pi}^2} T_0(\xi_t) \right] , \quad (14)$$

$$D_0^{NP} = \left\{ \frac{1}{4\sqrt{2}G_F F_{\tilde{\pi}}^2} F_0(y_t) + \frac{1}{3\sqrt{2}G_F F_{\pi}^2} [F_0(z_t) + 8F_0(\xi_t)] \right\} , \quad (15)$$

$$E_0^{NP} = \left\{ \frac{1}{4\sqrt{2}G_F F_{\tilde{\pi}}^2} I_0(y_t) + \frac{1}{3\sqrt{2}G_F F_{\pi}^2} [I_0(z_t) + 8I_0(\xi_t) + 9N_0(\xi_t)] \right\} , \quad (16)$$

$$E_0'^{NP} = \left\{ \frac{1}{8\sqrt{2}G_F F_{\tilde{\pi}}^2} K_0(y_t) + \frac{1}{6\sqrt{2}G_F F_{\pi}^2} [K_0(z_t) + 8K_0(\xi_t) + 9L_0(\xi_t)] \right\} , \quad (17)$$

where $y_t = m_t^{*2}/m_{\tilde{\pi}}^2$ with $m_t^* = (1 - \epsilon)m_t$, $z_t = (\epsilon m_t)^2/m_{\pi_1}^2$, $\xi_t = (\epsilon m_t)^2/m_{\pi_8}^2$, and

$$T_0(x) = -\frac{x^2}{8(1-x)} - \frac{x^2}{8(1-x)^2} \log[x] , \quad (18)$$

$$F_0(x) = \frac{47 - 79x + 38x^2}{108(1-x)^3} + \frac{3 - 6x^2 + 4x^3}{18(1-x)^4} \log[x] , \quad (19)$$

$$I_0(x) = \frac{7 - 29x + 16x^2}{36(1-x)^3} - \frac{3x^2 - 2x^3}{6(1-x)^4} \log[x] , \quad (20)$$

$$K_0(x) = -\frac{5 - 19x + 20x^2}{6(1-x)^3} + \frac{x^2 - 2x^3}{(1-x)^4} \log[x] , \quad (21)$$

$$L_0(x) = -\frac{4 - 5x - 5x^2}{6(1-x)^3} - \frac{x - 2x^2}{(1-x)^4} \log[x] , \quad (22)$$

$$N_0(x) = \frac{11 - 7x + 2x^2}{36(1-x)^3} + \frac{1}{6(1-x)^4} \log[x] . \quad (23)$$

The first term in Eq.(14) arises from the top-pion penguins, while the second and third term correspond to the color-singlet and color-octet technipion penguin respectively. For all four functions, the top-pion penguins always dominate absolutely[22].

In numerical calculations, we use the following parameters of the TC2 model as input parameter. Since the new physics contributions from technipions π_1^\pm and π_8^\pm are much smaller than those from top-pion $\tilde{\pi}^\pm$ within the reasonable parameter space, we here fix $m_{\pi_1} = 100\text{GeV}$ and $m_{\pi_8} = 200\text{GeV}$ for the sake of simplicity:

$$m_{\pi_1} = 100\text{GeV}, m_{\pi_8} = 200\text{GeV}, F_{\tilde{\pi}} = 50\text{GeV}, F_{\pi} = 120\text{GeV}, \epsilon = 0.05, \quad (24)$$

where F_π and $F_{\tilde{\pi}}$ are the decay constants for technipions and top-pions, respectively. For $m_{\tilde{\pi}}$, we consider the range of $m_{\tilde{\pi}} = 200 \pm 100$ GeV to check the mass dependence of branching ratios of two-body charmless hadronic B meson decays studied. All other relevant input parameters, such as the quark masses and form factors, *etc.*, are given in the Appendix.

Since the heavy charged pseudo-scalars appeared in TC2 model have been integrated out at the scale M_W , the QCD running of the Wilson coefficients $C_i(M_W)$ down to the scale $\mu = O(m_b)$ after including the NP contributions will be the same as in the SM. In the NDR scheme, by using the input parameters as given in Appendix and Eq.(24) and setting $\mu = 2.5$ GeV, we find that:

$$\begin{aligned} C_1 &= 1.1245, & C_2 &= -0.2662, & C_3 &= 0.0195, & C_4 &= -0.0441, \\ C_5 &= 0.0111, & C_6 &= -0.0535, & C_7 &= 0.0026, & C_8 &= 0.0018, \\ C_9 &= -0.0175, & C_{10} &= 0.0049, & C_g^{\text{eff}} &= 0.3735 \end{aligned} \quad (25)$$

where $C_g^{\text{eff}} = C_g + C_5$.

In this letter, the generalized factorization ansatz³ as being used in Ref.[9, 22] will be employed. For the studied seven B meson decay modes, we use the decay amplitudes as given in Ref.[8] without further discussion about details. We focus on estimating the new physics effects on these seven measured decay modes.

In the NDR scheme and for $SU(3)_C$, the effective Wilson coefficients can be written as [9]

$$C_i^{\text{eff}} = \left[1 + \frac{\alpha_s}{4\pi} \left(\hat{r}_V^T + \gamma_V^T \log \frac{m_b}{\mu} \right) \right]_{ij} C_j + \frac{\alpha_s}{24\pi} A'_i (C_t + C_p + C_g) + \frac{\alpha_{ew}}{8\pi} B'_i C_e, \quad (26)$$

where $A'_i = (0, 0, -1, 3, -1, 3, 0, 0, 0, 0)^T$, $B'_i = (0, 0, 0, 0, 0, 0, 1, 0, 1, 0)^T$, the matrices \hat{r}_V and γ_V contain the process-independent contributions from the vertex diagrams, and can be found, for example, in Refs.[9, 29]. The function C_t , C_p , and C_g describe the contributions arising from the penguin diagrams of the current-current $Q_{1,2}$, the QCD operators Q_3 - Q_6 , and the tree-level diagram of the magnetic dipole operator Q_{8G} , respectively. The explicit expressions of the functions C_t , C_p , and C_g can be found for example in Refs.[9, 22]. We here also follow the procedure of Ref.[7] to include the contribution of magnetic gluon penguin.

In the generalized factorization ansatz, the effective Wilson coefficients C_i^{eff} will appear in the decay amplitudes in the combinations,

$$a_{2i-1} \equiv C_{2i-1}^{\text{eff}} + \frac{C_{2i}^{\text{eff}}}{N_c^{\text{eff}}}, \quad a_{2i} \equiv C_{2i}^{\text{eff}} + \frac{C_{2i-1}^{\text{eff}}}{N_c^{\text{eff}}}, \quad (i = 1, \dots, 5) \quad (27)$$

where the effective number of colors N_c^{eff} is treated as a free parameter varying in the range of $2 \leq N_c^{\text{eff}} \leq \infty$, in order to model the non-factorizable contribution to the hadronic

³For recent discussions about the generalized factorization approach, one can see Ref.[29] and reference therein.

matrix elements. Although N_c^{eff} can in principle vary from channel to channel, but in the energetic two-body hadronic B meson decays, it is expected to be process insensitive as supported by the data [9]. As argued in Ref.[17], $N_c^{\text{eff}}(LL)$ induced by the $(V-A)(V-A)$ operators can be rather different from $N_c^{\text{eff}}(LR)$ generated by $(V-A)(V+A)$ operators. In this paper, however, we will simply assume that $N_c^{\text{eff}}(LL) \equiv N_c^{\text{eff}}(LR) = N_c^{\text{eff}}$ and consider the variation of N_c^{eff} in the range of $2 \leq N_c^{\text{eff}} \leq \infty$ since we here focus on the calculation of new physics effects.

In the B rest frame, the branching ratios $\mathcal{B}(B \rightarrow PP)$ can be written as

$$\mathcal{B}(B \rightarrow XY) = \frac{1}{\Gamma_{\text{tot}}} \frac{|p|}{8\pi M_B^2} |M(B \rightarrow XY)|^2, \quad (28)$$

where $\Gamma_{\text{tot}}(B_u^-) = 3.982 \times 10^{-13}$ GeV and $\Gamma_{\text{tot}}(B_d^0) = 4.252 \times 10^{-13}$ GeV obtained by using $\tau(B_u^-) = 1.653 ps$ and $\tau(B_d^0) = 1.548 ps$ [30], p_B is the four-momentum of the B meson, $M_B = 5.279$ GeV is the mass of B_u or B_d meson, and

$$|p| = \frac{1}{2M_B} \sqrt{[M_B^2 - (M_X + M_Y)^2][M_B^2 - (M_X - M_Y)^2]} \quad (29)$$

is the magnitude of momentum of particle X and Y in the B rest frame.

For the seven studied B meson decay modes, currently available measurements from CLEO, BaBar and Belle Collaborations [11, 12, 13, 14] are as follows:

$$\mathcal{B}(B \rightarrow \pi^+ \pi^-) = \begin{cases} (4.3_{-1.5}^{+1.6} \pm 0.5) \times 10^{-6} & [\text{CLEO}], \\ (9.3_{-2.1}^{+2.8 +1.2} \times 10^{-6} & [\text{BaBar}], \end{cases} \quad (30)$$

$$\mathcal{B}(B \rightarrow K^+ \pi^0) = \begin{cases} (11.6_{-2.7}^{+3.0 +1.4} \times 10^{-6} & [\text{CLEO}], \\ (18.8_{-4.9}^{+5.5} \pm 2.3) \times 10^{-6} & [\text{Belle}], \end{cases} \quad (31)$$

$$\mathcal{B}(B \rightarrow K^+ \pi^-) = \begin{cases} (17.2_{-2.4}^{+2.5} \pm 1.2) \times 10^{-6} & [\text{CLEO}], \\ (12.5_{-2.6}^{+3.0 +1.3} \pm 2.3) \times 10^{-6} & [\text{BaBar}], \\ (17.4_{-4.6}^{+5.1} \pm 3.4) \times 10^{-6} & [\text{BELLE}], \end{cases} \quad (32)$$

$$\mathcal{B}(B \rightarrow K^0 \pi^+) = (18.2_{-4.0}^{+4.6} \pm 1.6) \times 10^{-6} \quad [\text{CLEO}], \quad (33)$$

$$\mathcal{B}(B \rightarrow K^0 \pi^0) = \begin{cases} (14.6_{-5.1}^{+5.9 +2.4} \times 10^{-6} & [\text{CLEO}], \\ (21_{-7.8}^{+9.3 +2.5} \times 10^{-6} & [\text{BELLE}], \end{cases} \quad (34)$$

$$\mathcal{B}(B \rightarrow K^+ \eta') = \begin{cases} (80_{-9}^{+10} \pm 7) \times 10^{-6} & [\text{CLEO}], \\ (62 \pm 18 \pm 8) \times 10^{-6} & [\text{BaBar}], \end{cases} \quad (35)$$

$$\mathcal{B}(B \rightarrow K^0 \eta') = (89_{-16}^{+18} \pm 9) \times 10^{-6} \quad [\text{CLEO}]. \quad (36)$$

The measurements of CLEO, BaBar and BELLE Collaboration are consistent with each other within errors.

In Table 1, we present the theoretical predictions of the branching ratios for the seven $B \rightarrow PP$ decay modes in the framework of the SM and TC2 model by using the form factors from Baner, Stech and Wirbel (BSW) model[31] and Lattice QCD/QCD sum rule (LQQSR) model [32] form factors, as listed in the first and second entries respectively.

Table 1: Branching ratios (in units of 10^{-6}) of seven studied B decay modes in the SM and TC2 model by using the BSW and LQQSR form factors, with $k^2 = m_b^2/2$, $A = 0.81$, $\lambda = 0.2205$, $\rho = 0.12$, $\eta = 0.34$, $N_c^{\text{eff}} = 2, 3, \infty$ and $m_{\tilde{\pi}} = 200$ GeV, and by employing generalized factorization approach.

Channel	SM			TC2			$\delta\mathcal{B}$ [%]		
	2	3	∞	2	3	∞	2	3	∞
$B^0 \rightarrow \pi^+\pi^-$	9.03	10.3	12.9	9.20	10.4	13.1	1.9	1.8	1.6
	10.7	12.2	15.4	10.9	12.2	15.6	1.9	1.8	1.6
$B^+ \rightarrow K^+\pi^0$	12.1	13.5	16.7	19.6	21.8	26.5	63	61	59
	14.3	16.0	19.8	23.3	25.8	31.4	63	61	58
$B^0 \rightarrow K^+\pi^-$	17.7	19.6	23.8	24.2	26.7	32.0	37	36	35
	21.0	23.3	28.3	28.8	31.8	38.1	37	36	35
$B^+ \rightarrow K^0\pi^+$	20.0	23.3	30.7	27.8	32.8	44.1	39	41	44
	23.8	27.7	36.5	33.0	39.0	52.4	39	41	44
$B^0 \rightarrow K^0\pi^0$	7.22	8.25	10.6	7.88	9.28	12.5	9.3	13	18
	8.61	9.85	12.6	9.44	11.1	15.0	9.6	13	18
$B^+ \rightarrow K^+\eta'$	22.9	28.8	42.9	34.3	42.1	60.2	50	46	40
	26.3	33.1	49.3	39.3	48.3	69.2	50	46	40
$B^0 \rightarrow K^0\eta'$	22.0	28.3	43.1	33.0	41.5	61.4	50	47	43
	25.3	32.4	49.5	37.9	47.6	70.5	50	47	43

Theoretical predictions are made by using the central values of input parameters as given in Eq.(24) and the Appendix, and assuming $m_{\tilde{\pi}} = 200\text{GeV}$ and $N_c^{\text{eff}} = 2, 3, \infty$ in the generalized factorization approach. The branching ratios collected in the tables are the averages of the branching ratios of B and anti- B decays. The ratio $\delta\mathcal{B}$ describes the new physics correction on the decay ratio and is defined as

$$\delta\mathcal{B}(B \rightarrow XY) = \frac{\mathcal{B}(B \rightarrow XY)^{TC2} - \mathcal{B}(B \rightarrow XY)^{SM}}{\mathcal{B}(B \rightarrow XY)^{SM}} \quad (37)$$

By comparing the theoretical predictions with data, the following points can be understood:

- For $B_d^0 \rightarrow \pi^+\pi^-$ decay, the SM prediction is clearly larger than the CLEO measurement, but agree with BaBar measurement, while the BaBar measurement has a larger error than CLEO. The new physics contribution to this tree-dominated decay mode is negligibly small.
- For four $B \rightarrow K\pi$ decays, the SM predictions are agree with experimental measurements. In TC2 models, the theoretical predictions are generally larger than the

data but still agree with the data with 2σ errors[22] since both the theoretical and experimental errors are still large now.

- For $B_u^+ \rightarrow K^+\eta'$ and $B_d^0 \rightarrow K^0\eta'$ decay, the SM predictions are clearly much smaller than the data (especially the CLEO measurement). But the new physics enhancement can make the theoretical predictions in the TC2 model become agree with CLEO/BaBar data within one standard deviation.

The unexpectedly large $B \rightarrow K\eta'$ decay rates were firstly observed in 1997 [33], and confirmed recently with the full CLEO II and II.V samples [11]. The earlier SM predictions in the range of $(1 - 2) \times 10^{-5}$ are too small compared with experiment. In the framework of the SM, the $B \rightarrow K\eta'$ decays can be enhanced through [16] (i) the small running mass m_s at the scale m_b ⁴, (ii) the sizable $SU(3)$ breaking in the decay constant f_0 and f_8 , (iii) larger form factor $F_0^{B\eta'}(0)$ due to the smaller $\eta - \eta'$ mixing angle -15.4° rather than $\approx -20^\circ$, (iv) contribution from the η' charm content, and (v) constructive interference in tree amplitudes. However, as pointed out in Ref.[18, 7], the above mentioned enhancement is partially washed out by the anomaly effects in the matrix element of pseudoscalar densities, an effect overlooked before. As a consequence, the net enhancement is not very large: $\mathcal{B}(B^\pm \rightarrow K^\pm\eta') = (40 - 50) \times 10^{-6}$ as given in Ref.[21].

In the TC2 model, on the other hand, the new gluonic and electroweak penguins contribute through constructive interference with their SM counterparts and consequently provide the large enhancements, $\sim 50\%$ with respect to the SM predictions, as shown in Table 1. By using $F_0^{B\pi}(0) = 0.33$ and other input parameters as given in the Appendix, one finds numerically that

$$\mathcal{B}(B^\pm \rightarrow K^\pm\eta') = \begin{cases} (20 - 52) \times 10^{-6} & \text{in SM,} \\ (30 - 71) \times 10^{-6} & \text{in TC2,} \end{cases} \quad (38)$$

$$\mathcal{B}(B^0 \rightarrow K^0\eta') = \begin{cases} (19 - 52) \times 10^{-6} & \text{in SM,} \\ (29 - 73) \times 10^{-6} & \text{in TC2,} \end{cases} \quad (39)$$

where the effects induced by the uncertainties of major input parameters have been taken into account. The SM prediction is still smaller than the CLEO result but agree with the BaBar measurement⁵. In Fig.1, we plot the mass-dependence of $\mathcal{B}(B^+ \rightarrow K^+\eta')$ and $\mathcal{B}(B^0 \rightarrow K^0\eta')$ in the SM and TC2 model. The short-dashed line in Fig.1 shows the SM predictions with $N_c^{\text{eff}} = 3$. The dot-dashed and solid curve refers to the branching ratios in the TC2 model for $N_c^{\text{eff}} = 3$ and ∞ , respectively. The upper dots band corresponds to the data with 2σ errors: $\mathcal{B}(B^\pm \rightarrow K^\pm\eta') = (75 \pm 20) \times 10^{-6}$ (average of CLEO and BaBar result) and $\mathcal{B}(B^0 \rightarrow K^0\eta') = (89_{-36}^{+40}) \times 10^{-6}$ (CLEO only). It is evident that the theoretical predictions in the TC2 model are agree well with CLEO/BaBar data within one standard deviation.

⁴However, a rather small m_s is not consistent with recent lattice calculations.

⁵One should note that the error of BaBar result is much larger than that of CLEO result.

Since $B_d^0 \rightarrow \pi^+\pi^-$ decay is a tree-dominated decay mode, the new physics correction induced through loop diagrams should be very small, as shown in Table 1. The CLEO measurement of this mode puts a very stringent constraint on the form factor $F_0^{B\pi}(0)$: $F_0^{B\pi}(0) = 0.20 \pm 0.04$ as given in Ref.[34]. In the SM, this smaller form factor will lead to two difficulties:

1. First, the predicted $B \rightarrow K\pi$ branching ratios will be too small when compared with the data since their decay rates depend on the form factors $F_0^{B\pi}(0)$ and $F_0^{BK}(0)$. We know that the form factor $F_0^{BK}(0)$ cannot deviate too much from $F_0^{B\pi}(0)$, otherwise the $SU(3)$ -symmetry relation $F_0^{BK} = F_0^{B\pi}$ will be badly broken.
2. Second, the predicted $B \rightarrow K\eta'$ branching ratios will be also too small in the SM since the branching ratio $\mathcal{B}(B \rightarrow K\eta')$ depends on both the form factor $F_0^{B\pi}(0)$ and $F_0^{B\eta'}$. A small $F_0^{BK}(0)$ leads to a small $F_0^{B\eta'}$ and in turn small branching ratios of $B \rightarrow K\eta'$ decays. If we use the relation [8],

$$F_{0,1}^{B\eta'} = F_{0,1}^{B\pi} \left(\frac{\sin \theta_8}{\sqrt{6}} + \frac{\cos \theta_0}{\sqrt{3}} \right), \quad F_{0,1}^{B\eta} = F_{0,1}^{B\pi} \left(\frac{\cos \theta_8}{\sqrt{6}} - \frac{\sin \theta_0}{\sqrt{3}} \right) \quad (40)$$

to define $F_0^{B\eta'}$ with $\theta_0 = -9, 1^\circ$ and $\theta_8 = -22.2^\circ$ [8], the SM prediction for the branching ratio $\mathcal{B}(B \rightarrow K\eta')$ will be decreased by about 26%. In Table 2, we show the branching ratios of seven studied decay modes obtained by using $F_0^{B\pi}(0) = 0.20$ instead of $F_0^{B\pi}(0) = 0.33$ while keep all other input parameters remain the same as being used in Table 1.

In TC2 model, however, the decrease induced by using smaller $F_0^{B\pi}(0)$ will be compensated by large new physics enhancement and therefore restore the agreement between the theoretical predictions and the data, as illustrated in Fig.2 for the decay $B \rightarrow K\eta'$. By using $F_0^{B\pi}(0) = 0.20 \pm 0.04$, one finds that

$$\mathcal{B}(B^\pm \rightarrow K^\pm \eta') = \begin{cases} (12 - 45) \times 10^{-6} & \text{in SM,} \\ (20 - 62) \times 10^{-6} & \text{in TC2,} \end{cases} \quad (41)$$

$$\mathcal{B}(B^0 \rightarrow K^0 \eta') = \begin{cases} (11 - 44) \times 10^{-6} & \text{in SM,} \\ (20 - 61) \times 10^{-6} & \text{in TC2,} \end{cases} \quad (42)$$

where the effects of major uncertainties have been taken into account.

In Fig.2, we plot the mass dependence of $\mathcal{B}(B^+ \rightarrow K^+ \eta')$ and $\mathcal{B}(B^0 \rightarrow K^0 \eta')$ in the SM and TC2 model by using $F_0^{B\pi}(0) = 0.20$ instead of 0.33 (while all other input parameters are the same as in Fig.1). The short-dashed line in Fig.2 shows the SM predictions with $N_c^{\text{eff}} = 3$. The dot-dashed and solid curve refers to the branching ratios in the TC2 model for $N_c^{\text{eff}} = 3$ and ∞ , respectively. The upper dots band corresponds to the CLEO/BaBar data with 2σ errors. It is easy to see that (a) the gap between the SM predictions of $B \rightarrow K\eta'$ decay rates and the data is enlarged by using $F_0^{B\pi}(0) = 0.20$

Table 2: Branching ratios (in units of 10^{-6}) of seven studied B decay modes in the SM and TC2 model by using the BSW form factors with $F_0^{B\pi}(0) = 0.20$ instead of $F_0^{B\pi}(0) = 0.33$, assuming $k^2 = m_b^2/2$, $A = 0.81$, $\lambda = 0.2205$, $\rho = 0.12$, $\eta = 0.34$, $N_c^{\text{eff}} = 2, 3, \infty$ and $m_{\bar{\pi}} = 200$ GeV, and by employing generalized factorization approach.

Channel	SM			TC2			$\delta\mathcal{B}$ [%]		
	2	3	∞	2	3	∞	2	3	∞
$B^0 \rightarrow \pi^+\pi^-$	3.32	3.77	4.75	3.38	3.83	4.83	1.9	1.8	1.6
$B^+ \rightarrow K^+\pi^0$	5.12	5.77	7.25	9.09	10.1	12.5	77.6	75.8	71.9
$B^0 \rightarrow K^+\pi^-$	6.49	7.20	8.73	8.90	9.80	11.7	37.1	36.2	34.6
$B^+ \rightarrow K^0\pi^+$	7.34	8.55	11.3	10.2	12.0	16.2	38.9	40.7	43.7
$B^0 \rightarrow K^0\pi^0$	2.20	2.47	3.11	1.94	2.27	3.07	-12.0	-8.2	-1.5
$B^+ \rightarrow K^+\eta'$	16.9	21.7	33.3	25.6	32.0	47.0	51.7	47.3	41.0
$B^0 \rightarrow K^0\eta'$	16.2	21.0	32.8	24.5	31.1	46.7	51.7	47.8	42.5

instead of 0.33, and (b) the new physics enhancement therefore becomes essential for the theoretical predictions to be consistent with CLEO/BaBar result within 2σ errors.

From Table 2, it is easy to see that the new physics enhancement to first three $B \rightarrow K\pi$ decays and $B \rightarrow K\eta'$ decays are still large in size and play an important role to boost the corresponding branching ratios to be consistent with experimental measurements.

For the $B \rightarrow K^0\pi^0$ decay mode, the SM predictions are always smaller than the data although the error of the data is still very large, as can be seen from Tables 1-2. For the case of using $F_0^{B\pi}(0) = 0.33$, the new physics contribution in TC2 model provide a (10 – 20)% enhancement. For the case of using $F_0^{B\pi}(0) = 0.20$, however, the new physics contribution in TC2 model result in a (2 – 12)% decrease. We currently are not sure that whether there is a discrepancy between the theory and the data for this decay mode. This is an open problem now, further refinement of the data will clear this point soon.

In short, we here studied the new physics contributions to the seven observed $B \rightarrow PP$ decay modes by employing the effective Hamiltonian with generalized factorization. In this letter, particular attention is devoted to the details of $B \rightarrow K\eta'$ decays, and to the discussions about currently known mechanisms to enhance this decay mode. We made the numerical calculation by using both $F_0^{B\pi}(0) = 0.33$ as given in the ordinary BSW model, as well as $F_0^{B\pi}(0) = 0.20 \pm 0.04$ preferred by the CLEO data of $B \rightarrow \pi^+\pi^-$. We presented the numerical results in Tables 1-2 and Figs.1-2. We also discussed the difficulties induced by using the smaller $F_0^{B\pi}(0)$ and shown that one can accommodate the data of $\pi^+\pi^-$, $K^+\pi$, and $K^0\pi^+$ simultaneously after taking into account the new physics contributions. But we are still not sure if there is a discrepancy between the theory and the data for $B \rightarrow K^0\pi^0$ decay mode.

By using whether $F_0^{B\pi}(0) = 0.20 \pm 0.04$ or 0.33, we always found that the new physics

enhancements to $B \rightarrow K\eta'$ decays are significant in size, and hence the theoretical predictions of $\mathcal{B}(B \rightarrow K\eta')$ in the TC2 model agree with CLEO/BaBar data within 2σ errors. This seems to be a simple and plausible new physics interpretation for the observed $\eta'K$ puzzle.

Appendix: Input parameters

In this appendix we present the relevant input parameters.

- Input parameters of electroweak and strong coupling constant, gauge boson masses, light meson masses, \dots , are as follows (all masses in unit of GeV) [8, 30]

$$\begin{aligned} \alpha_{em} &= 1/128, \alpha_s(M_Z) = 0.118, \sin^2 \theta_W = 0.23, G_F = 1.16639 \times 10^{-5} (GeV)^{-2}, \\ M_Z &= 91.188, M_W = 80.42, m_{B_d^0} = m_{B_u^\pm} = 5.279, m_{\pi^\pm} = 0.140, \\ m_{\pi^0} &= 0.135, m_\eta = 0.547, m_{\eta'} = 0.958, m_{K^\pm} = 0.494, m_{K^0} = 0.498. \end{aligned} \quad (43)$$

- For the elements of CKM matrix, we use Wolfenstein parametrization, fix the parameters A, λ and ρ to their central values: $A = 0.81, \lambda = 0.2205, \rho = 0.12$, but varying η in the range of $\eta = 0.34 \pm 0.08$.
- We first treat the internal quark masses in the loops as constituent masses: $m_b = 4.88\text{GeV}, m_c = 1.5\text{GeV}, m_s = 0.5\text{GeV}, m_u = m_d = 0.2\text{GeV}$. Second, we use the current quark masses for m_i ($i = u, d, s, c, b$) which appear through the equation of motion when working out the hadronic matrix elements. For $\mu = 2.5\text{GeV}$, one found [8]: $m_b = 4.88\text{GeV}, m_c = 1.5\text{GeV}, m_s = 0.122\text{GeV}, m_d = 7.6\text{MeV}, m_u = 4.2\text{MeV}$. For the mass of heavy top quark we use $m_t = \overline{m}_t(m_t) = 168\text{GeV}$.
- For the decay constants of light mesons, the following values will be used in the numerical calculations (in the units of MeV):

$$\begin{aligned} f_\pi &= 133, f_K = 158, f_\eta^u = f_\eta^d = 78, f_{\eta'}^u = f_{\eta'}^d = 68, \\ f_\eta^c &= -0.9, f_{\eta'}^c = -0.23, f_\eta^s = -113, f_{\eta'}^c = 141. \end{aligned} \quad (44)$$

where $f_{\eta^{(\prime)}}^u$ and $f_{\eta^{(\prime)}}^s$ have been defined in the two-angle-mixing formalism with $\theta_0 = -9.1^\circ$ and $\theta_8 = -22.2^\circ$ [35].

- The relevant form factors are [8]

$$F_0^{B\pi}(0) = 0.33, F_0^{BK}(0) = 0.38, F_0^{B\eta}(0) = 0.145, F_0^{B\eta'}(0) = 0.135, \quad (45)$$

in the BSW model [31], and

$$F_0^{B\pi}(0) = 0.36, F_0^{BK}(0) = 0.41, F_0^{B\eta}(0) = 0.16, F_0^{B\eta'}(0) = 0.145, \quad (46)$$

in the LQSR approach. And the momentum dependence of form factor $F_0(k^2)$ was defined in Ref.[31] as $F_0(k^2) = F_0(0)/(1 - k^2/m^2(0^+))$. The pole masses being used to evaluate the k^2 dependence of form factors are $m(0^+) = 5.73$ GeV for $\bar{u}b$ and $\bar{d}b$ currents, and $m(0^+) = 5.89$ GeV for $\bar{s}b$ currents.

ACKNOWLEDGMENTS

Authors are very grateful to D.S. Du, K.T. Chao, C.S.Li, C.D. Lü, Y.D. Yang and M.Z.Yang for helpful discussions. Z.J. Xiao acknowledges the support by the National Natural Science Foundation of China under the Grant No.19575015 and 10075013, the Excellent Young Teachers Program of Ministry of Education, P.R.China and the Natural Science Foundation of Henan Province under the Grant No. 994050500.

References

- [1] P.F. Harrison and H.R. Quinn, Editors, *The BaBar Physics Book*, SLAC-R-504, 1998.
- [2] R. Fleischer and J. Matias, Phys.Rev.**D61**, 074004(2000).
- [3] D. Atwood and A. Soni, Phys.Rev.Lett. **81**, 3324(1999); D. Atwood and A. Soni, Phys.Rev. **D59**, 013007 (1999);
- [4] Z.J. Xiao, C.S. Li and K.T. Chao, Phys.Lett. **B473**, 148(2000); Z.J. Xiao, C.S. Li and K.T. Chao, Phys.Rev. **D62**, 094008(2000).
- [5] H. Simma and D. Wyler, Phys.Lett. **B272**, 395 (1991); G. Kramer, W.F. Palmer and H. Simma, Nucl.Phys. **B428**,77(1994); Z.Phys. **C66**, 429(1995); R. Fleischer, Phys.Lett. **B321**, 259(1994); Z.Phys. **C62**, 81(1994); G. Kramer and W.F. Palmer, Phys.Rev. **D52**, 6411(1995); N.G. Deshpande and X.G. He, Phys.Lett. **B336**, 471(1994); G. Kramer, W.F. Palmer and Y.L. Wu, Commun.Theor.Phys. **27**, 457(1997); C.-W. Chiang and L. Wolfenstein, Phys. Rev. **D61**, 074031(2000).
- [6] D. Du and L. Guo, Z.Phys. **C75**, 9(1997); D. Du and L. Guo, J. Phys. **G23**, 525(1997).
- [7] A. Ali, C. Greub, Phys.Rev **D57**, 2996 (1998); A. Ali, J. Chay, C. Greub and P. Ko, Phys.Lett. **B424**, 161(1998).
- [8] A. Ali, G. Kramer and C.D. Lü, Phys.Rev. **D58**, 094009(1998).
- [9] Y.H. Chen, H.Y. Cheng, B. Tseng and K.C. Yang, Phys.Rev. **D60**, 094014(1999); Y.H. Chen, H.Y. Cheng, B. Tseng, Phys.Rev. **D59**, 074003(1999).
- [10] M. Bishai *et al.*, CLEO Collaboration, CLEO CONF 99-13, hep-ex/9908018; T.E. Coan *et al.*, CLEO Collaboration, CLEO CONF 99-16, hep-ex/9908029; Y. Kwon *et al.*, CLEO Collaboration, CLEO CONF 99-14, hep-ex/9908039.
- [11] S.J. Richichi *et al.*, CLEO Collaboration, Phys.Rev.Lett. **85**, 520(2000);
- [12] D. Cronin-Hennessy *et al.*, CLEO Collaboration, Phys.Rev.Lett. **85**, 515(2000); C.P. Jessop *et al.*, CLEO Collaboration, Phys.Rev.Lett. **85**, 2881 (2000).
- [13] J. Olsen, BaBar Collaboration, talk given at DPF'2000, Columbus Ohio, USA, BaBar-talk-00/27.
- [14] A. Abashian *et al.*, Belle Collaboration, talks given at ICHEP'2000, Osaka, Japan, 2000, Conf0005, Conf-0006, Conf0007;
- [15] D. Jaffe, Talk Presented at BNL Particle Physics Seminar, 2000, CLEO-Talk 00-10.

- [16] H.-Y. Cheng, hep-ph/0008285; W.-S. Hou, hep-ph/0009197, talk 07g-02, ICHEP 2000, Osaka, Japan, 2000.
- [17] H.Y. Cheng and B. Tseng, Phys.Rev.**D58**, 094005(1998);
- [18] A.L. Kagan and A.A. Petrov, hep-ph/9707354.
- [19] D. Atwood and A. Soni, Phys.Lett. **B405**, 150(1997); I. Halperin and A. Zhitnisky, Phys.Rev.Lett. **80**, 438(1998); W.S. Hou and B. Tseng, Phys.Rev.Lett. **80**, 434(1998); H.Y. Cheng and B. Tseng, Phys.Rev.**D58**, 094005(1998).
- [20] F. Yuan and K.T. Chao, Phys.Rev. **D56**, R2495(1997); D.S. Du, C.S. Kim and Y.D. Yang, Phys.Lett. **B426**, 133 (1998).
- [21] H.Y. Cheng and B. Tseng, Phys.Rev.**D62**, 054029(2000).
- [22] Z.J. Xiao, W.J. Li, L.B. Guo and G.R. Lu, Eur.Phys.J. C18, 681(2001).
- [23] C.T. Hill, Phys. Lett. **B345**, 483(1995); K. Lane and E. Eichten, Phys.Lett. **B352**, 382 (1995). D. Kominis, Phys. Lett. **B 358**, 312 (1995).
- [24] Z.J. Xiao, C.S.Li and K.T. Chao, Phys.Rev. D63, 074005 (2001).
- [25] G. Buchalla, A.J. Buras and M.E. Lautenbacher, Rev.Mod.Phys. **68**, 1125 (1996).
- [26] K. Lane, report presented at the 28th International Conference on High Energy Physics, Warsaw (July 1996), ICHEP 96:367-378.
- [27] G. Buchalla, G. Burdman, C.T. Hill and D. Kominis, Phys.Rev.**D53**, 5185 (1996);
- [28] Z.J.Xiao, L.X. Lü, H.K. Guo and G.R. Lu, Eur. Phys. J. **C7**, 487(1999); Z.J. Xiao, C.S. Li and K.T. Chao, Eur. Phys. J. **C10**, 51(1999).
- [29] H.-Y. Cheng, Hsiang-nan Li and K.C. Yang, Phys.Rev. **D60**, 094005 (1999).
- [30] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. **C15**,1 (2000).
- [31] M. Bauer and B. Stech, Phys.Lett. **B152**, 380 (1985);
M. Bauer, B. Stech and M. Wirbel, Z. Phys. **C29**, 637 (1985); *ibid*, **C34**, 103 (1987).
- [32] For more details about LQQSR form factors, one can see: J.M. Flynn and C.T. Sachrajda, hep-lat/9710057, and reference therein.
- [33] B.H. Behrens *et al.*, CLEO Collaboration, Phys.Rev.Lett. **80**, 3710 (1998).
- [34] H.Y. Cheng, hep-ph/9912372.
- [35] T. Feldmann and P. Kroll, Eur.Phys.J. **C5**, 327 (1998).

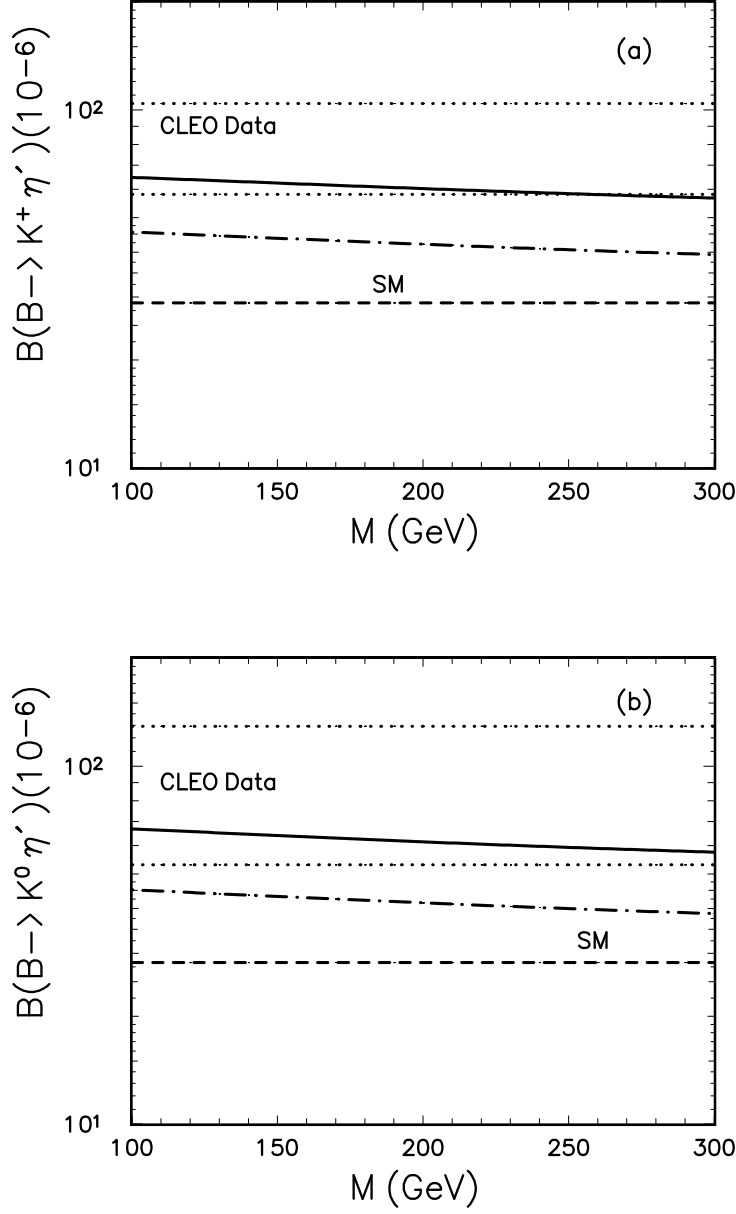


Figure 1: Plots of branching ratios of decays $B^+ \rightarrow K^+ \eta'$ (1a) and $B^0 \rightarrow K^0 \eta'$ (1b) versus mass $m_{\tilde{\pi}}$ in the SM and TC2 model with $F_0^{B\pi}(0) = 0.33$. The short-dashed line shows the SM predictions with $N_c^{\text{eff}} = 3$. The dot-dashed and solid curve refers to the branching ratios in the TC2 model for $N_c^{\text{eff}} = 3$ and ∞ , respectively. Theoretical uncertainties are not shown here. The dots band corresponds to the CLEO/BaBar data with 2σ errors: $\mathcal{B}(B^\pm \rightarrow K^\pm \eta') = (75 \pm 20) \times 10^{-6}$ and $\mathcal{B}(B^0 \rightarrow K^0 \eta') = (89^{+40}_{-36}) \times 10^{-6}$.

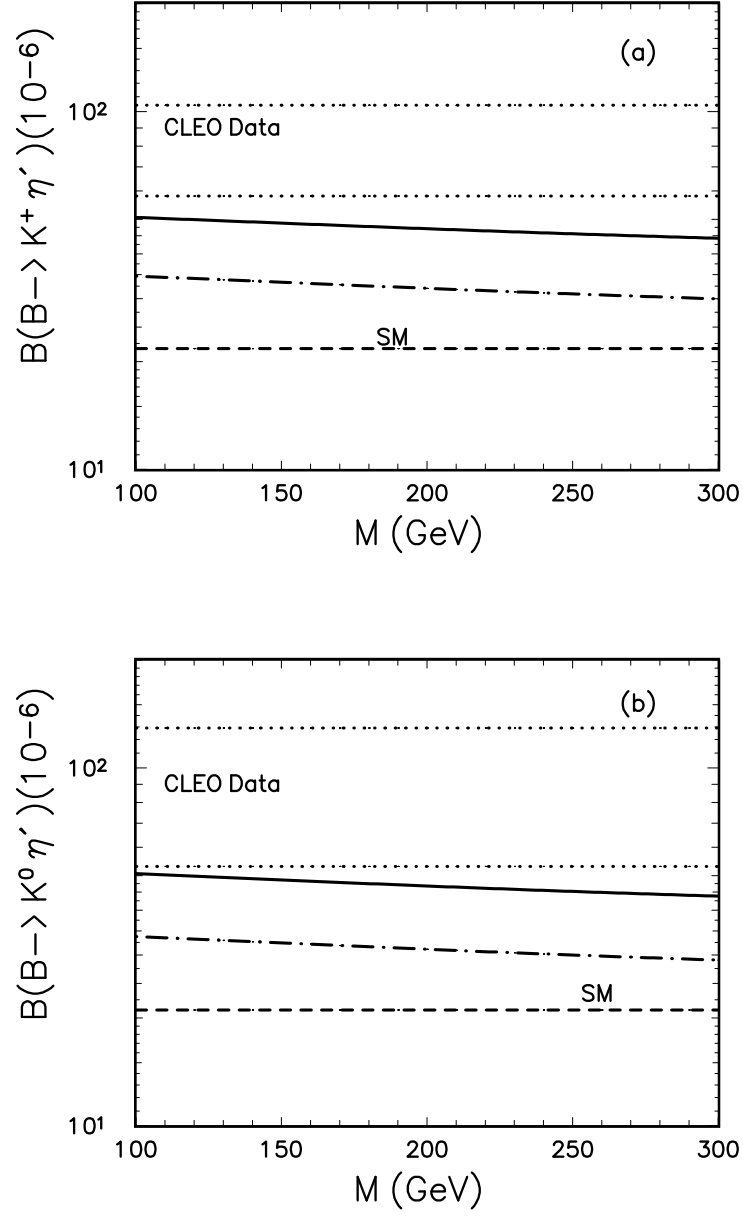


Figure 2: Same as Fig.1 but for $F_0^{B\pi}(0) = 0.20$ instead of 0.33.